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SUBJECT: NASA Contract NASr-217, Quarterly Status Report for the period 1 December 1965 through 28 February 1966.

Gentlemen:

This informal three-month status report covers the recent research activities on "Nonlinear Aspects of Combustion Instability in Liquid Propellant Rocket Motors".

The various interrelated phases of this research are listed in the order indicated in the work statement associated with Contract NASr-217.

I. Stability-Limits Testing

Following the investigation into the higher mode regimes associated with the "distributed" combustion rocket designs (typically the like-on-like type injection) a series of tests on the quarter-size square-motor hardware have been run. These tests were conceived as a means of separating the effects of the number of elements from the element spacing in the injector design. In particular, it was hoped that the differences in behavior might be resolved between 4 x 4 injector patterns (where, characteristically, pulsing was necessary to initiate instability) and the 2 x 2 patterns (where spontaneous instability zones were the rule and pulsing failed to extend those boundaries).

The tests with the quarter-size hardware use a 2 x 2 injector design where the orifices are identical to those of the 4 x 4 injector. Using the Type IV injector design, which minimizes fan end-impingement, spontaneous instability was found at lengths greater than 20 inches, a condition similar to that found with full-size 2 x 2 injectors where orifice diameters were twice as large. At mixture ratios near 2.5 (LOX/ALC.) pulsing was required to initiate instability (also noted at 24 inches). At still higher mixture ratios spontaneous instability returned. The rocket motor was stable at 16 inches.

In Type II tests (i.e., an injector with unlike fan end-impingement) spontaneous instability has been absent with pulsing required at 24 inches.

As with the previous injector, stable operation (even with pulsing) was found at O/F ratios near 2.5. With the limited data now available no final conclusions can be drawn at this time. However, these zones will be investigated more fully following the tests described in Phase X.

Preliminary designs have been completed for the acoustic liner hardware for the 9-inch diameter rocket motor. Inserts will allow adjustment of cavity and port sizes. A single prototype cavity design is being placed in existing hardware for evaluation of thermal compatibility. A program of testing that would include fuel-on-oxidizer impinging designs (existing spuds found to be highly unstable in unbaffled hardware) is currently planned.

II. Nonlinear Displacement Studies

The inability to gain quantitative vaporization rate data from the existing cold flow apparatus has led to the following modifications.

A droplet generator similar to that used by J. A. Nicholls et al, which is presently under construction, will replace the former injector as a means to introduce the fluid into the chamber. The generator will be physically attached to the voice coil of a speaker and, driven at the proper frequency, will result in a uniform array of droplets of initial diameter of approximately 200 microns. Changing the frequency and/or the generator hypodermic tubing diameters allow the initial droplet diameters to be varied over a wide range. Altering the injection velocity affords the ability to subject the droplets to a greater or lesser number of transverse acoustic oscillations. The tests will be conducted in a closed chamber at a series of radial positions and at a variety of pressures. The apparatus can also, if the need for such data appears pertinent, be equipped with a heater which will allow tests to be conducted at elevated temperatures to enhance vaporization.

It is intended that by photographic observations, a correlation between vaporization rates in a stagnant chamber and in a resonant chamber will be obtained. Projecting into the future, it is not unreasonable to suggest, that the equipment could also be used for droplet combustion studies.

As a corollary to this study, recent attempts have been made, with a high speed camera, to photograph the spray fans from one of the injectors of the LOX/ALC 9" diameter rocket engine. The purpose of this experiment is to study via framing and streak photography, the velocity and direction of transverse gas motion in the engine. Observations were made through a 1" diameter quartz window mounted close to the injector face. The injector closest to the window was blocked off and the fan opposite the window was photographed. With this set-up it was possible to photograph a section of the fan approximately 2" long. Due to several factors, however, the pictures were of insufficient clarity to permit even gross observations. In this regard the following is proposed: through the use of an auxiliary tank and feed system, which is presently under construction, the spray fan to be observed will have dissolved in the fuel, a sodium salt (Sodium salicylate, N_aC,H_5O_3, would appear to be satisfactory).

By utilizing the correct interference filter at the window it will be possible to transmit to the camera only that light resulting from the excitation of the sodium D radiation. If a polarizing filter is also used it will be possible to eliminate reflections from the chamber walls; a prime reason for the poor quality of the earlier pictures.

With the above technique it will be possible to observe the behavior of the combustion gases in the vicinity of the injector under both stable and unstable conditions. A refinement of the above would be to place another window opposite the existing one and with the aid of backlighting and the proper selection of filters expose color film. This would enable one to observe both liquid and gas behavior in the engine.

III. Oscillating Nozzle Flow

A method of crossplotting the results of the nozzle admittance calculations in a form which is useful for publication is being developed by the Guggenheim Laboratories computer group. Also the presentation of the theory is being written for the same publication.

The presentation will include discussions of the nozzle admittance theory for nozzles of circular and rectangular (or thin annular) cross-sections, of the asymptotic theory (low Mach number) theory for conical nozzles, and of the computer programs used to calculate admittance coefficients and the wave forms of the flow properties. This publication (an AGARD monograph) should be the needed reference for listings of nozzle admittance coefficients and associgeometrical scaling rules.

IV. Nonlinear Transverse Studies

The Ph.D. thesis of Mr. Ben Zinn should be issued as a technical report within the next two months. This work was a theoretical study of nonlinear transverse (actually three-dimensional) instability. The eigenfunction expansion technique was employed which is well known to be a cumbersome, slowly-converging approach. This disallowed calculations which were very extensive in scope and limited numerical results to a rather small parameter range. Certain restrictive assumptions were necessary to transform the problem into a manageable form: namely, concentrated combustion zone at the injector end and irrotational flow. The result was that to linear order the stability predictions were different from those of Scala and Reardon who treated the case of irrotational flow with distributed combustion.

For these reasons, it is desirable to attempt a new approach to the transverse problem. Several are being tried. One in particular reduces the algebra by ordering the combustion, mean flow, and nozzle effects into one large term which appears only to higher order. This approximation has been already shown valid in the work, "A Shock Wave Model of Unstable Rocket Combustors" by Sirignano and Crocco.

Hopefully, this simplification will allow the consideration of the case of rotational flow and distributed combustion. Also the study of conical chambers and annular chambers may be allowed.

A numerical study of transient transverse wave propagation is being initiated. In the first attempt, mean flow, combustion, and nozzle effects are being neglected. The main desire is to determine whether shock waves may form in the transverse case or are the final stable solutions as those predicted by Maslen and Moore. The numerical computations will be simplified by a convenient change of frame of reference.

Longitudinal Shock Wave Instability With Distributed Combustion

One of the major problems in this study is the development of a suitable stability criterion when nonlinear effects including both combustion and shock wave phenomena are involved. Toward this end the integral, time average stability condition introduced by Cantrell and Hart and extended by Crocco to include non-isentropic flow, mass sources, and shock waves has been further extended to the general case where sources of mass and momentum, specie diffusion, and arbitrary numbers and order of chemical reactions are present. The nth order stability condition thus developed involves solutions to the (n - 1) order equations except when shock waves are present. In the case of shock waves the nth order stability criterion involves an nth order entropy change across the charge.

The form of the equations is general enough to include a stability criterion for gas rockets as well as liquid propellant rockets.

It remains to be shown how the stability condition mentioned may be used in the solution of the particular problem of shock wave instability with distributed combustion. However, it is felt that the stability criterion developed will probably be instrumental in any solution of the problem.

V. Start Transients

During the report period, two potential methods of solution of differential equations were explored and discarded and a third is being examined at this time. The problem has been simplified to one that separates combustion and gas dynamic phenomena. The gas dynamic solution of wave motion through a time variant mean flow field was pursued using the method of characteristics and later the WKBJ method was considered for the general solution of the potential function. Use of the method of characteristics results in characteristic curves which are not linear in the physical plane. A knowledge of the complete flow field is required to make use of this method. Therefore a general solution of the wave equation with time-variant coefficients was attempted with a modification of the WKBJ method for partial differential equations. This form of solution requires one to obtain the potential function for the flow field obtaining the velocity from its derivatives. The solution to obtain the potential function was considered to be unnecessarily complicated and for this reason, it was recommended that the attempted solution in this form be dropped.

The next approach to the problem is an attempt at a direction solution of the pressure and velocity field by making use of the momentum, energy, and continuity equation in their standard uncombined form. The objective is to linearize these equations so that with proper manipulation, a set of second order equations in one variable will be obtained. This method of solution is being developed at the present time.

VI. Higher Mach Numbers

Efforts are being made to develop an approach to the stability analysis which will be useful for higher Mach number cases. Both the direct differential equation approach and the integral approach are being considered. The most important thing here is to realize which properties can be expanded in a series in Mach number and which properties cannot be. As was already known the entropy could not in general be expanded since entropy waves propagate at the particle velocity and therefore have a wavelength which is inversely proportional to the Mach number. Recently, it has been shown that the gas velocity has similar behavior due to the irrotationality. Therefore, the gas velocity is not expandable. Since entropy and vorticity have only higher order effects on pressure, the pressure is expandable. Following these notions a solution of the problem is being attempted.

VII. Droplet Wake Studies

A pseudo-wake, namely, a two-dimensional jet mixing with concentrated chemical reaction in the oscillatory environment is being studied and developed. A boundary layer concept is being used. It is found that even in steady case, the similar solution is inappropriate for representing the region immediate downstream of the initial zone. The similar solution is only the asymptotic form in the region sufficiently far downstream. Also a consideration of the physical phenomena shows that a significant portion of combustion should occur in the initial zone. With such difficulty, an attempt for solving partial differential equations instead of ordinary differential equations should be made for the steady case. A weak dependence of properties on x (one of the independent variables in transformed coordinates) might be a good assumption. For the unsteady parts, using concentration of fuel or oxidizer as the independent variable would hopefully simplify the boundary conditions (particularly at the flame).

VIII. Droplet Population Wave Studies

The purpose of this phase of the research is to investigate one possible coupling mechanism between the injection process and oscillations observed in rocket chambers (not necessarily high-frequency phenomena).

Since the last quarterly report the systematic study of the droplet population wave phenomena (previously described) has been initiated. Thus far the streak pictures have all been taken at a location 1 7/8" downstream of the injector and with a ΔP of 50 psi across the injector (a .040 inch diameter, 90^o angle, like-on-like spud). Pictures have been taken at chamber pressures ranging from 40 to 115 psia. The first objective of this study was to confirm the results previously obtained at 115 psia and then to extend the work to other pressures with the hope of finding a frequency change with pressure. Such a change would be expected since at one atmosphere the frequency of droplet population oscillations was of the order of 2000-3000 cps.

Based on the amount of data available at present these aims have been achieved. A frequency of about 120 cps was confirmed at a chamber pressure of 115 psia, and the frequency was seen to change smoothly as the pressure was lowered. At P_c = 40 psia the frequency was found to be about 400 cps. From the data available at present a chamber pressure of 65 psia produces a droplet population frequency equal to the chamber resonant frequency (1L mode = 340 cps). Further tests will be run at or near this pressure to more accurately determine droplet population variations. When the ratio of the maximum number of droplets to the minimum number in a wave is examined it is found that there is a slight increase (from 2.5 to 3.5) at this resonance chamber pressure. However, this increase is based upon a limited quantity of data. If confirmed this would indicate that chamber geometry as well as the droplet breakup processes could influence droplet population waves. It is also planned to artifically drive the chamber at its resonant frequency using the siren system while maintaining the 65 psia condition. This would further probe the extent of this "coupling". It was previously found at P_c = 115 psia that the siren had no effect.

IX. Early Combustion Behavior

Several tests have been run on the low pressure kinetics apparatus to investigate possible differences in the early combustion behavior of ethanol and RP-1 type fuels. Such data are deemed necessary to properly interpret spinning tangential mode instability tests previously recorded. The results of these preliminary kinetic reactor tests have indicated that although the ethanol combustion reaction rate is rather slow (compared to hydrogen-air for example) the reaction does begin close to the point of injection. Vaporized heptane (representing a hydrocarbon fuel), on the other hand, exhibits a delayed combustion reaction. Following the delay (or induction period) the rate of reaction was higher than that of the ethanol. In the preliminary tests described the reaction was not completed within the duct. Methane tests showed a similar induction period but the reaction was completed within the duct.

Additional tests are currently in progress to determine the role of the oxidizer concentration on the reaction rates of the two types of propellants. Since difficulty arises in using RP-1 (because a vaporized fuel is required and RP-1 is a blend which results in selective distillation) heptane was used in the preliminary tests. Additional tests with heptane, methane, pentane and isopentane are contemplated with varying oxidizer concentration.

It is felt that using a variety of hydrocarbon fuels a better estimate may be made as to the characteristics of RP-1. The use of certain of these fuels in the transverse rocket hardware would also appear desirable to check the validity of the kinetic reactor extrapolations.

X. Property Measurements in Rocket Motors

To survey the axial speed of sound distribution as well as to more clearly define the degree and location of energy addition to a passing wave, six Dynisco pressure transducers are being utilized in the square-motor. The transducers (PT49CF Models) are spaced at approximately three-inch intervals extending from 1 to 16½ inches from the injector face. Only with a matched set of transducers could sufficient accuracy be hoped for in the measurement of initial or half amplitude points on the first and subsequent shock-type waves generated by the pulse gun (or spontaneously in certain rocket tests).

Difficulties have arisen from several sources in these tests. The lines from the rocket cell were dissimilar, four being coaxial type and two twisted pair. That condition has been remedied this week with the move to an updated recording facility. Also a multiple recording technique has been used (playback from one recorder to another, remotely located, was used to expand the time scale) with problems resulting on one channel. The a.c. amplifiers necessary with strain gauge transducer outputs are also being improved from a phase standpoint. Additional tests are planned this week in which pulses originating at several locations in the rocket chamber will be used to minimize wave steepening effects, another possible cause of errors in precise time measurements in previous tests.

The test results to date clearly indicate the effect of combustion coupling which apparently enhances the energy of the incident wave (shown as a reduction in the decay rate of the wave heading toward the injector) while causing little change in the decay rate of the reflecting wave. The standard for these comparisons was helium-filled square-motor tests which were set up so as to provide a comparable gas density and speed of sound environment as experienced in the hot firings.

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